1976ApJ...204..131W

THE ASTROPHYSICAL JOURNAL, 204:131–140, 1976 February 15
© 1976. The American Astronomical Society. All rights reserved. Printed in U.S.A.

ISOTOPIC ABUNDANCES OF Hg IN MERCURY STARS INFERRED FROM Hg II λ3984

RICHARD E. WHITE,* ARTHUR H. VAUGHAN, JR.,† G. W. PRESTON,† AND J. P. SWINGS‡
Received 1975 June 30

ABSTRACT

Wavelengths of Hg II λ3984 in 30 Hg stars are distributed uniformly from the value for the terrestrial mix to a value that corresponds to nearly pure ^{204}Hg. The wavelengths are correlated loosely with effective temperatures inferred from $Q(UBV)$. Relative isotopic abundances derived from partially resolved profiles of λ3984 in ι CrB, χ Lup, and HR 4072 suggest that mass-dependent fractionation has occurred in all three stars. We suppose that such fractionation occurs in all Hg stars. Accordingly, we present a scheme whereby isotopic compositions can be inferred from a comparison of stellar wavelengths and equivalent widths with those calculated for a family of fractionated isotopic mixes. Theoretical profiles calculated for the derived isotopic composition agree well with high-resolution interferometric profiles obtained for three of the stars.

Subject headings: stars: abundances — stars: peculiar A stars

I. INTRODUCTION

Bidelman's (1962) identification of Mg II as the atomic species responsible for λ3984 in the spectra of the Mn stars has been supported by subsequent detection of Hg I λ4358 and λ5460 in χ Lup and ι CrB (Bidelman 1966) and by partial resolution of the isotopic structure of λ3984 in HR 4072, χ Lup, and ι CrB (Dworetsky *et al.* 1970; Preston 1971). The isotopic patterns in the above stars indicate abnormally large relative abundances of the heavier Hg isotopes, particularly ^{204}Hg, but Bidelman reported a centroid wavelength for κ Cnc that corresponds more nearly to that expected for the terrestrial mix. Thus it appears that major variations in the relative abundances of Hg isotopes occurs among the Hg Mn stars (which we shall call Hg stars in all that follows).

The isotopic splitting of λ3984, ~0.07 Å between components due to successive even-numbered nuclei (Mrozowski 1940), precludes resolution of isotopic components in stars for which $v \sin i \gtrsim 3$ km s^{-1}. Only a few known Hg stars satisfy this stringent requirement. Therefore, for most stars we are restricted to the more limited information that can be derived from the centroid wavelengths of unresolved isotopic blends. Wavelengths of λ3984 for eight Hg stars have been compiled from the literature by Guthrie (1971), but the observational material is neither extensive nor homogeneous. Because of the interest that attends the unexpected variety of isotopic compositions of Hg inferred from the behavior of λ3984, we undertook the study of a larger sample of stars. Some of our results were presented in abstract form previously (Preston *et al.* 1971).

* Goddard Space Flight Center, Institute for Space Studies, New York, New York.

† Hale Observatories, Carnegie Institution of Washington, California Institute of Technology.

‡ Institut d'Astrophysique, Université de Liège.

II. OBSERVATIONAL DATA

a) Photographic Survey

A sample of 30 Hg stars was chosen from a variety of sources, chiefly Osawa (1965), Cowley *et al.* (1969), and Cowley (1972). In order to achieve measurement errors that are small relative to the anticipated range in wavelengths, the sample was limited to stars for which $v \sin i < 40$ km s^{-1}. Only two $v \sin i$ values exceed 30 km s^{-1}. The sample includes five single-lined binaries, four double-lined binaries with a Hg star primary, and two double-lined binaries in which both components are Hg stars. The spectroscopic characteristics of the group are hardly homogeneous. All possess abnormally strong lines of Mn II and Hg II, but the degree of enhancement varies greatly from star to star. In addition enhanced lines of some of the elements P, Sc, Ga, Sr, Y, Zr, and Pt generally are present. Hg λ3984 has been reported in magnetic Ap stars of the SiCrEu species, but we have excluded such stars from this study because of possible severe contamination by the lines Fe I λ3983.96 and Cr I λ3983.90 that are expected to be present in their spectra. Although not previously classified as a Hg star, ν Cnc was included because it satisfies the loose criteria described above.

Series of spectrograms (Pb series, 4.5 Å mm^{-1}) were obtained for each star with the coudé spectrograph of the 5 m telescope over an interval of 12 months. The spectra, widened 0.8 mm, were recorded on baked IIa-O emulsion. The minimum number of observations for any star was four, and the average number was eight. Roughly half of the sample could be observed during any given night. The spread in times of observation was intended to minimize differential systematic errors in wavelength from star to star that might arise due to seasonal or nightly variations in the performance of the spectrograph. No such effects were detected.

All of the spectrograms were measured by Miss Sylvia Burd. For each spectrogram a radial velocity

© American Astronomical Society • Provided by the NASA Astrophysics Data System

TABLE 1

SUMMARY OF DATA FOR MERCURY STARS

HD	HR/Name	−Q	T_e (Q) (10^3 °K)	v sin i (km s^{-1})	W_{3984} (mÅ)	No. of Spectrograms	λ_c 3980+ (Å)	σ_λ (mÅ)	q	Log η	Log Nf (Log N_H = 12)	Notes
1909	89	0.25	12.4	13	108	14	3.995	3	1.2	2.7	4.3	SB1
3322	149	.33	13.4	28	108	7	3.937	11	0.0	2.3	3.8	
4335	205	.23	12.2	23	123	8	4.000	8	1.3	2.9	4.5	
11291	2 Per	.26	12.5	22	101	13	3.928	4	−0.2	2.2	3.9	SB1
11753	φ Phe	.10	10.9	13	25:	6	4.044	8	1.9	1.2	3.1	SB1?
16004	746	.27	12.7	26	101	9	3.944	7	0.0	2.2	3.8	
27376	41 Eri p	....	....	12	72	9	4.007	10	1.3	....	....	SB2
27376	41 Eri s	....	....	12	46	9	4.049	10	2.7	....	....	SB2
33904	μ Lep	.30	13.0	20	106	8	3.935	4	−0.1	2.3	3.8	
35548	1800	.16	11.4	6	84	8	4.000	4	1.2	2.3	4.0	
58661	2844	.35	13.7	27	144	9	3.929	4	−0.2	2.9	4.4	
75333	14 Hya	.28	12.8	32	103	9	3.957	8	0.4	2.3	3.8	
77350	ν Cnc	.08	10.7	20	32	7	4.029	9	1.5	1.3	3.2	
78316	κ Cnc	.35	13.7	6	85	5	3.954	5	0.3	1.9	3.4	SB1
89822	4072	.09	10.8	< 3	100	6	4.011	2	1.5	2.7	4.5	SB2
110073	ℓ Cen	.36	13.8	17	44	5	3.972	14	0.5	1.2	2.8	SB1
129174	π Boo A	.32	13.3	16	139	11	3.948	2	0.2	2.8	4.3	
141556	χ Lup	.08	10.7	< 3	59	9	4.052	5	3.0	2.5	4.3	SB2
143807	ι CrB	.14	11.3	< 3	59	12	3.999	4	1.0	1.6	3.5	
144206	υ Her	.24	12.3	11	108	8	3.982	3	0.9	2.5	4.1	
145389	φ Her	.23	12.2	12	57	15	4.016	4	1.4	1.9	3.6	
161701	6620	.37	14.0	16	40	10	3.976	10	0.6	1.2	2.7	SB2
172044	6997	.41	14.6	40	132	8	3.928	10	−0.2	2.7	4.2	
172883	7028	.17	11.6	26	....	4	4.012	26	....	....	....	
173524	46 Dra p	(.22)	(12.2)	≤ 5	88	8	4.011	6	1.5	2.5	....	SB2
173524	46 Dra s	(.22)	(12.2)	≤ 5	52	8	4.023	6	1.6	1.9	....	SB2
174933	112 Her	.36	13.8	≤ 5	82	4	3.983	4	0.9	2.1	3.6	SB2
182308	7361	.45	15.3	≤ 5	113	9	3.932	5	−0.1	2.4	3.8	
190229	7664	.41	14.6	11	66	7	3.967	7	0.5	1.6	3.1	SB1
202149	8118	.26	12.5	28	42	5	3.969	20	0.5	1.2	2.8	
207857	8349	.38	14.2	15	115	6	3.962	3	0.6	2.5	3.9	
221507	β Scl	.27	12.7	25	118	9	3.990	5	1.1	2.8	4.4	

derived from 20 to 40 lines of Si II, Ti II, Cr II, Mn II, and Fe II in the region λλ3850–4530 was used to correct the measured Hg II wavelength to its rest value. The mean values of the centroid wavelength λ_c and their mean errors σ are given in columns (8) and (9) of Table 1 together with other pertinent information. The adopted *UBV* colors are for the most part averages of values tabulated by Blanco *et al.* (1970). Effective temperatures were calculated from $Q = (U - B) - 0.72(B - V)$ by use of the calibration by Schild *et al.* (1971). The equivalent widths of λ3984 were derived from microphotometry of spectrograms used in this study (two per star). The values of $v \sin i$ were estimated by visual comparison of these spectrograms with those of a set of sharp-lined standard stars (Preston, unpublished); for three stars (χ Lup, ι CrB, HR 4072), previous estimates from higher dispersion spectrograms were adopted.

b) *Wavelength Errors*

We expect that random errors in λ_c should be largest for stars with large $v \sin i$ and/or small W_{3984}. This is confirmed by Figure 1 in which the standard deviation of a single measurement, σ_1, is plotted versus $v \sin i / W_{3984}$ for each star. The abscissa is roughly proportional to the reciprocal of line depth. From the correlation in Figure 1, we conclude that random measurement errors due to characteristics of the individual stellar spectra are more important than those of instrumental origin for $\sigma_1 \gtrsim 0.01$ Å.

In Table 2 we compare the Pb wavelengths of λ3984 and two Si II lines treated as unknowns with those

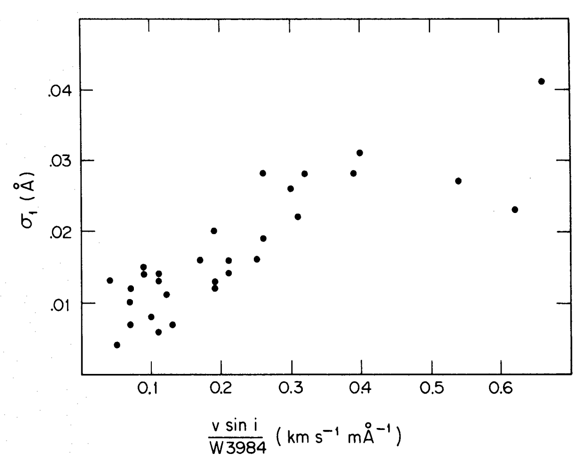

FIG. 1.—The dependence of the standard deviation of a single wavelength determination on $v \sin i$ and W_{3984}. The abscissa is roughly proportional to the reciprocal of line depth.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1976ApJ...204..131W

1976ApJ...204..131W

TABLE 2

COMPARISON OF WAVELENGTHS OBTAINED WITH DIFFERENT INSTRUMENTS

	$\Delta\lambda$ (Å)			
LINE	Pb − EC	Pb − Ce	Pb − Pa	Pb − lab.
Hg II λ3984...	−0.0003(3)	−0.0004(22)	−0.0058(5)	...
Si II λ3856....	+0.0096(3)	+0.0075(12)	−0.0032(6)	−0.005
Si II λ4130....	−0.0127(3)	−0.0045(22)	−0.0005(6)	−0.004
Average......	−0.0011	−0.0005	−0.0032	−0.0045

obtained from 4.0 Å mm^{-1} EC (Lick), 4.3 Å mm^{-1} Ce (Mount Wilson), and 2.2 Å mm^{-1} Pa (Palomar) coudé spectrograms, and also with the laboratory wavelengths of the Si II lines given in the *Revised Multiplet Table*. The numbers of EC, Ce, and Pa spectrograms available for the program stars used in the comparisons are given in parentheses. These spectrograms were measured by Sylvia Burd by the same procedures used for the Pb series. The average differences at the bottom of Table 2 indicate that if any systematic correction should be applied to our wavelengths it is probably positive and smaller than 0.01 Å.

c) *Interferometric Data*

The two-channel coudé scanner of the Mount Wilson 100 inch (2.5 m) telescope, equipped with a pressure-scanned Fabry Perot interferometer, was used to obtain detailed profiles of the Hg II λ3984 line in a small sample of the brighter Hg stars selected for low rotational broadening. The equipment provides a half-peak bandwidth of about 30 mÅ, and the scan increment was about 14 mÅ, which is sufficient to resolve the isotopic structure but too coarse to resolve the intrinsic line widths when $v \sin i \approx 0$.

The observations of each star consisted of one or two scans per night, repeated on several different nights. A wavelength reference line Fe I λ3983.960 (hollow cathode source) was scanned repeatedly in the course of each night to calibrate absolute wavelengths. Wavelength intervals were determined from measured gas-pressure intervals. The individual scans obtained for each star were corrected for photomultiplier dark current, transformed with appropriate wavelength shifts to a common rest frame, combined, and artificially smoothed. In the case of the spectroscopic binaries κ Cnc and 112 Her, it was necessary to allow for orbital changes in radial velocity in order to combine the data. The results are presented in Figure 2 and further discussed in § IV*e*.

The wavelength calibration procedures employed at the telescope were designed to remove instrumental effects due to temperature changes or other instabilities in the equipment. The internal consistency of calibration was tested by computing the cross-correlation of intensity as a function of wavelength-offset between each scan and the combined mean of all scans of a given star. The maximum of each cross-correlation should appear at zero offset if there are no differential zero-point wavelength errors. The scan-to-scan and night-to-night offsets in a given run were found to be well defined with values typically in the range ±0.005 Å, i.e., negligible. In the case of ι CrB, however, we found a systematic wavelength offset of about 37 mÅ (2.8 km s^{-1}) between sets of observations separated by an interval of 6 months. Such a shift is consistent with the observed dispersion in radial velocity among 4.5 Å mm^{-1} coudé spectrograms of ι CrB, but our data are insufficient to establish a period if the star is a velocity variable, as appears possible. The observations with discordant velocities are shown separately in Figure 2.

An analysis of the residual intensity differences between individual scans and the mean yields an estimate of the internal standard deviations of the mean intensities in a 30 mÅ bandwidth near the line centers (indicated by error bars in Fig. 2). These are about twice the deviations attributable to photon statistics, indicating that seeing-induced fluctuations are imperfectly compensated. The overall precision is sufficient in the case of ι CrB to show details attributable almost entirely to the contributions of individual isotopes. Virtually the same contributors appear in 112 Her if allowance is made for rotational broadening (see § IV*e*). A relatively greater contribution of light isotopes appears in κ Cnc.

III. RESULTS

The λ_c values in Table 1 are distributed rather uniformly over a range (0.12 Å) that exceeds typical mean errors by more than an order of magnitude. The upper bound of the distribution, ~λ3984.05, defined by χ Lup, ν Cnc, and the secondary component of 41 Eri is only slightly smaller than the wavelength for ^{204}Hg (λ3984.07). The lower bound, ~λ3983.93, defined by a half-dozen stars differs little from either the centroid of the straight mean of the isotopic components or the mean of components weighted by terrestrial abundances.

a) *The λ_c versus Q Diagram*

Early in this study we noticed a tendency for large λ_c's to be associated with the cooler stars. This is illustrated by the plot of λ_c versus Q in Figure 3. The data points are largely confined to the upper left and lower right quadrants. Division of the sample into two wavelength groups at λ3983.990 produces two Q groups that overlap by an amount that hardly exceeds

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1976ApJ...204..131W

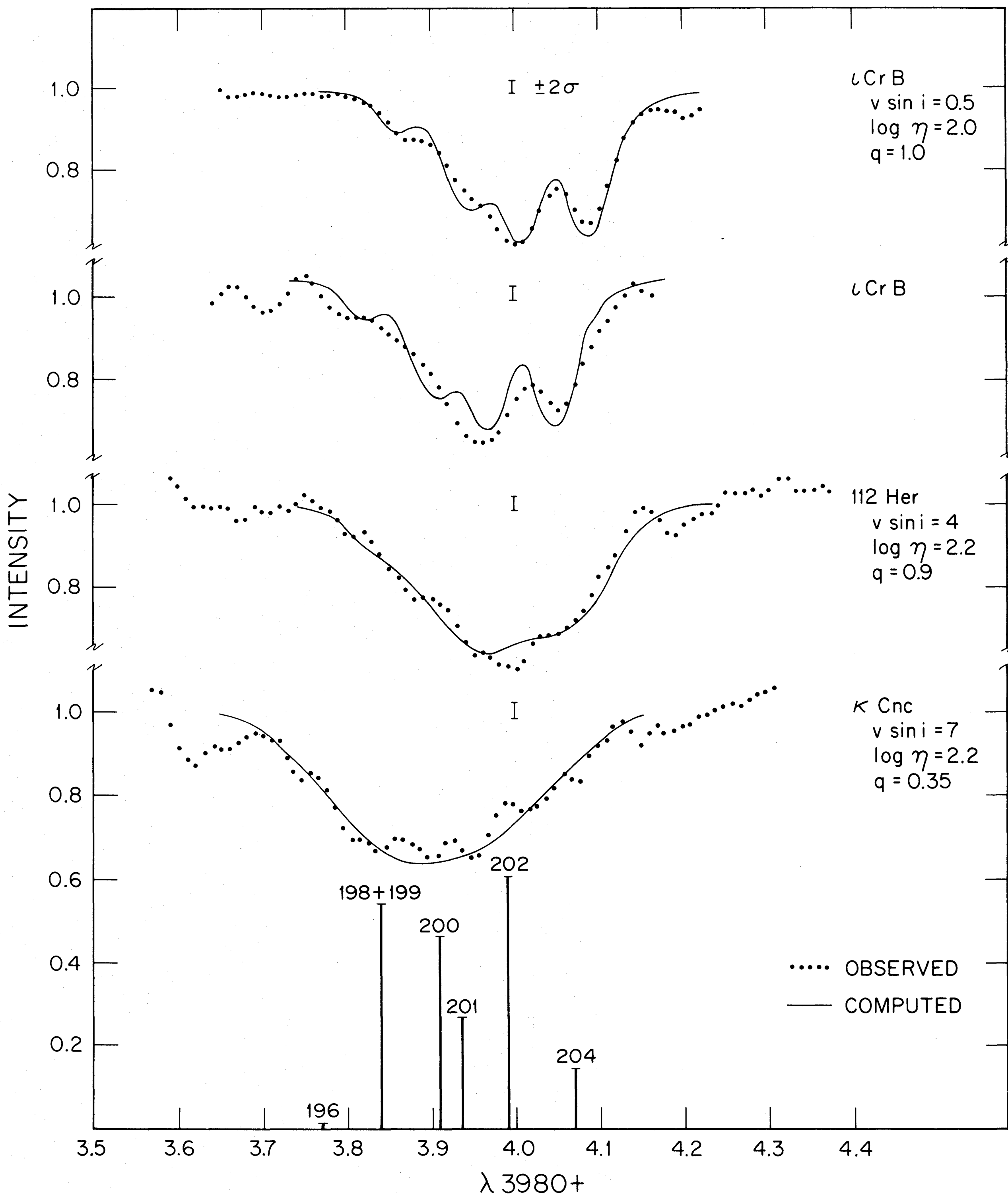

FIG. 2.—Profiles of Hg II λ3984 for three stars observed with a Fabry-Perot interferometer (*dotted curves*). The theoretical profiles (*solid curves*) are those computed for fractionation products of the terrestrial isotopic mixture as described in § IV*e*. Agreement with the observed profiles lends support to the fractionation hypothesis. Two independent observations are shown for ι CrB (see § II*c*). Vertical bars at bottom indicate wavelengths and intensities of isotopic components for the terrestrial mixture ($q = 0$).

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1976ApJ...204..131W

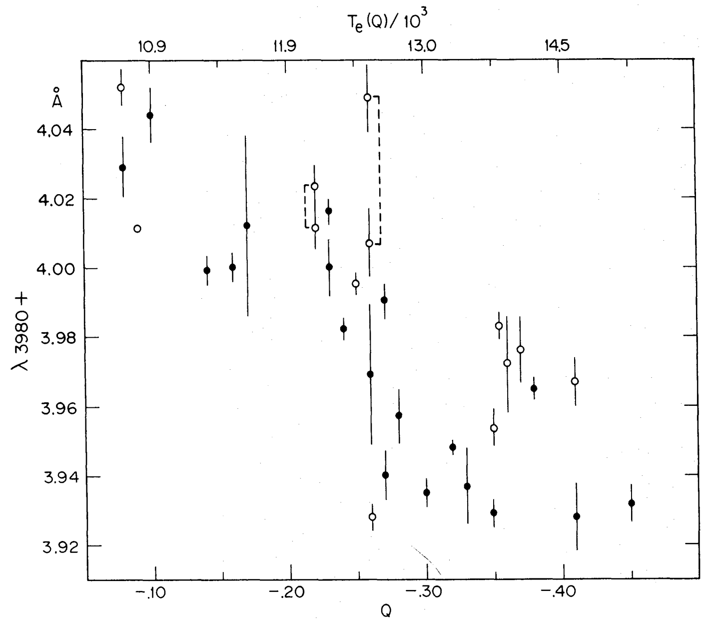

FIG. 3.—A plot of measured centroid wavelength versus Q for 33 Hg stars. Vertical bars denote mean errors. Filled and open circles denote single stars and components of spectroscopic binaries, respectively. Dotted lines connect components of the double-lined binaries 46 Dra and 41 Eri which are plotted at the positions of their observed Q values. The Q for 41 Eri is uncertain because of a close visual companion.

the observational errors in Q. Other characteristics of the two groups are given in Table 3. Of these the most interesting concerns platinum. Pt II lines are present in spectra of nine of the 15 stars in the cool group and in none of the 17 members of the hot group. In all nine Pt stars the wavelengths of Pt II λ4046 exceed the terrestrial value by amounts comparable with the shifts obtained for Hg II λ3984 in these stars (Dworetsky and Vaughan 1973). As in the case of λ3984, the shifts for Pt II λ4046 are plausibly interpreted as an isotope effect. Thus a majority of the cool group appear to possess overabundances of the heavy isotopes of both Hg *and* Pt. Finally, we note that the ionization potentials of Pt II and Hg II are 18.6 eV and 18.8 eV, respectively, and the observed lines for both species arise from 4 eV levels. Thus the Pt/Hg abundance ratio must be systematically greater in the cool group.

Alternatively, we may treat Figure 3 as an imperfect correlation between λ_c and Q. The correlation coefficient of the regression of λ_c against Q is $r = 0.75$: that is, $100r^2 = 56$ percent of the variance of λ_c in our sample can be accounted for by an assumed linear relation between λ_c and Q. For a multiple regression that also includes the possible dependencies on $v \sin i$ and W_λ suggested by Table 3 the correlation coefficient is slightly larger, $r = 0.84$. Saturation effects may produce a correlation of λ_c with W_λ (see § IV and Fig. 5), but the reason for a correlation of λ_c with $v \sin i$ remains obscure, and we are reluctant to discuss the significance of the latter analysis further at the present time.

b) *Possibility of Blends at λ3984*

The range and temperature dependence of λ_c described above would be of diminished interest if they were caused by contaminating lines of some unknown element. It is impossible to prove that this is not the case, but we argue below that it is highly unlikely.

1. The search for lines of singly ionized elements at λ3984 has proven fruitless. We have inspected published line lists of all the elements through Bi by use of the bibliographies of Moore (1945, 1968, 1969). There are no published data for Rh II, Ag II, and Ir II near λ4000. We found two coincidences, Nb II λ3983.94 and Hf II λ3984.02, but both are weak lines in rich spectra

TABLE 3

AVERAGE PROPERTIES OF Hg STARS DIVIDED INTO TWO GROUPS BY Hg II WAVELENGTH

λ_c	T_e	$v \sin i \pm$ |A.D.| (km s^{-1}) Single	SB1 + SB2	All	W_{3984} (Å)	PERCENT WITH Pt II LINES
≥3983.99....	≲12500	16 ± 8	9 ± 4	13 ± 7	73 ± 26	60
< 3983.99....	≳12500	23 ± 8	13 ± 6	19 ± 8	96 ± 25	0

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1976ApJ...204..131W

that contain hundreds of stronger lines.[1] We have not searched for lines of doubly ionized atoms in a systematic manner other than to verify that there are no coincidences for such ions in the *Revised Multiplet Table* and, in particular, none for Hg III or Mn III. A complete search is not possible because there are no published lists near λ4000 for third spectra of about half of the elements. In view of the progressive elevation of energy levels along isoelectronic sequences (White 1934) we do not expect many strong transitions of doubly ionized atoms near λ4000 in stars with $T_e \approx$ 12,000 K unless much richer singly ionized spectra are present. We have similar negative expectations for lines of neutral elements, and have confirmed that no such coincidences exist in the *M.I.T. Wavelength Tables* or the lists of arc spectra of 70 elements by Meggers *et al.* (1961), except for Cr I λ3983.906 and Fe I λ3983.960. The ultimate line Cr I λ4254 has $W_\lambda \approx 15$ mÅ in χ Lup and HR 4072 (Dworetsky 1971), and is undetectable in the hotter Hg stars: Cr I λ3938 must be of negligible strength. Fe I λ3983.960 probably *is* present and may contribute as much as 10 mÅ in the cooler Hg stars. However, it cannot produce either the range or the temperature dependence of λ_c.

2. At least two blending lines are required to produce the variety of profile structures encountered in χ Lup, ι CrB, κ Cnc, and 112 Her if relative isotopic abundances are constant among the Hg stars. Of 550 lines on λλ3600–4600 measured by Dworetsky (1971) in the spectrum of χ Lup, only 18 (3%) are unidentified. The strongest has $W_\lambda = 11$ mÅ, and the average is 6 mÅ. Of 16 unidentified lines in HR 4072 (Dworetsky 1971), the strongest has $W_\lambda = 15$ mÅ, and the average is 8 mÅ, i.e. some 10 times weaker than λ3984 in typical Hg stars. For a density of unidentified lines ~ 0.02 Å^{-1} the probability of a chance coincidence of a line of any strength within ± 0.05 Å at λ3983.98 is $\sim 10^{-3}$. The probability of additional coincidences is correspondingly smaller.

3. Dworetsky *et al.* (1970) used the experimental *f*-value of Hg I λ4358 (Penkin 1964) and the equivalent widths of λ4358 and λ3984 in χ Lup and HR 4072 to derive an astrophysical absorption *f*-value $\sim 3 \times 10^{-3}$ for λ3984. If a contaminant produced as much as half of the observed equivalent width of λ3984 in χ Lup, this *f*-value would have to be smaller by a factor of about 7. So small an *f*-value seems to be incompatible with the work of Paschen (1928) who, in a laboratory study of 300 Hg II lines, lists only three with intensities greater than that of λ3984. Of these, two are $2\,^2P^o$–$1\,^2S$ transitions to the ground state that should be strong. The laboratory spectrum was produced by a hollow cathode discharge with He as the exciting gas. Paschen noted that resonance excitation of $3\,^2P_{5/2}$ by He I $2\,^3P^o$ may be responsible for the anomalous strength of Hg II λ6149, but there is no resonance excitation for the $2\,^2P^o{}_{5/2}$ upper level of λ3984, i.e., the laboratory strength of λ3984 probably reflects its substantial *f*-value rather than overpopulation of its upper level in the discharge tube.

In conclusion, we believe that it is more reasonable to seek an explanation for the variable isotopic compositions of Hg in Hg stars than it is to insist on variable blending by lines of an unidentified substance.

IV. ANALYSIS

a) The Case for Isotopic Fractionation

Isotopic abundance anomalies can be produced by atypical nuclear processing or by isotope separation. Evidence summarized elsewhere (Cameron 1971; Preston 1974) indicates that isotope anomalies of the Hg stars are not likely to be the result of nucleosynthesis in stellar interiors or atmospheres. Therefore, we look for evidence of the fractionation that results from an isotope separation process. All such processes (e.g., centrifugation, condensation, diffusion) depend only on isotopic mass differences for their success, although the functional form of the mass dependence varies from process to process. One such process, diffusion induced by radiation pressure, already has been proposed as the cause of the Hg anomalies (Michaud *et al.* 1974).

Relative isotopic abundances of Hg have been estimated for only three stars—ι CrB, χ Lup, and HR 4072 (Dworetsky *et al.* 1970; Preston 1971). The dependence of these estimates on atomic weight A is shown in Figure 4. The ordinate is the logarithm of the separation factor

$$\alpha = \frac{[N(A)/N(202)]_*}{[N(A)/N(202)]_\odot} \quad (1)$$

in which abundances are arbitrarily reckoned in units of ^{202}Hg atoms. The quantity α is the factor by which the ratio of isotope A to 202 in the star is increased or decreased relative to its terrestrial value. A roughly linear relation between $\log \alpha$ and A is found for the two stars (ι CrB and HR 4072) for which more than

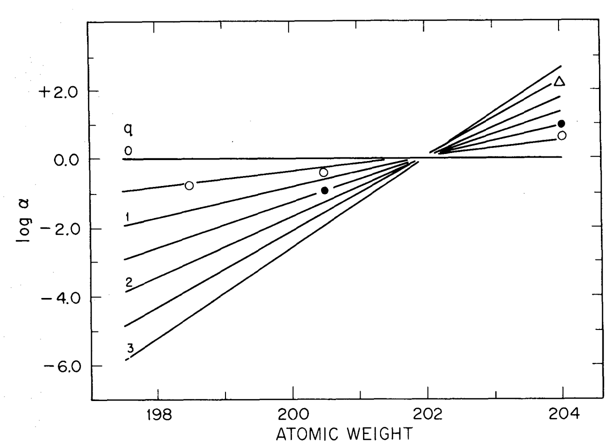

FIG. 4.—The variation of the separation factor α with atomic weight for ι CrB (*open circles*), HR 4072 (*filled circles*), and χ Lup (*triangle*). The straight lines represent isotopic mixtures defined by eq. (2).

[1] Referee Charles Cowley calls attention to Ne I λ3984.05 as a third unlikely identification.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1976ApJ...204..131W

TABLE 4

WAVELENGTHS AND NORMALIZED ABUNDANCES GENERATED BY EQUATION (2)

A	196	198	199*		200	201*		202	204	
q					g_i					$\lambda(q) = \Sigma g_i \lambda_i$
−0.25	0.0045	0.1788	0.0990	0.1347	0.2471	0.0404	0.0698	0.1973	0.0283	....
0.00	.0015	.1000	.0714	.0971	.229	.048	.083	.300	.070	3.930
0.25	.0004	.0476	.0438	.0596	.1806	.0486	.0840	.3382	.1472	3.958
0.50	.0001	.0193	.0223	.0311	.1213	.0418	.0732	.4277	.2634	3.985
0.75	....	.0068	.0103	.0140	.0703	.0311	.0538	.4067	.4070	4.008
1.00	....	.0021	.0041	.0056	.0360	.0204	.0353	.3414	.5552	4.027
1.25	....	.0006	.0015	.0020	.0167	.0121	.0210	.2598	.6863	4.042
1.50	....	.0002	.0005	.0007	.0072	.0067	.0116	.1839	.7893	4.052
1.75	....	....	.0002	.0002	.0030	.0035	.0061	.1236	.8632	4.059
2.00	....	....	....	.0001	.0012	.0018	.0031	.0806	.9132	4.064
2.25	....	....	....	....	.0004	.0009	.0016	.0514	.9457	4.066
2.50	....	....	....	....	.0002	.0004	.0008	.0323	.9663	4.068
2.75	....	....	....	....	.0001	.0002	.0004	.0202	.9792	....
3.00	....	....	....	....	....	.0001	.0002	.0125	.9872	....
λ3980+	3.769	3.838	3.838	3.849	3.909	3.930	3.941	3.990	4.071	

* The hyperfine components of the odd isotopes are treated as if they were due to individual (fictitious) isotopes with abundance ratios equal to the laboratory intensity ratios.

two isotopic abundances were estimated. Data points at 198.5 and 200.5 represent sums of abundances 198 + 199 and 200 + 201 that cannot be separated in the stellar spectra. Although the data are insufficient to establish the linearity of the relations with certainty, the monotonic increases of α with A strongly support the notion that fractionation, of varying degree, has occurred in all three stars. Therefore, in view of the large range of observed λ3984 wavelengths, we believe it reasonable to postulate a family of isotopic mixtures for Hg stars defined by

$$\log \alpha = q(A - 202) \log_{10} e \qquad (2)$$

in which q is a dimensionless mix parameter. We then infer the isotopic compositions of the stars by comparing properties of the profiles of λ3984 generated by these mixes with the stellar data. The mixes, given in Table 4, are plotted as the fan of straight lines in Figure 4.

In applying equation (2), we have treated the hyperfine components of the odd isotopes as if they were due to individual (fictitious) isotopes of the mixture with abundance ratios equal to the laboratory intensity ratios given by Mrozowski (1940). Thus, since the hyperfine components of a given isotope are represented by the same A, the correct hyperfine intensity ratios are preserved for all values of q. Table 4 lists the Hg isotopes, their laboratory wavelengths, and normalized relative abundances for values of q ranging from -0.25 to $+3.0$. The abundances for $q = 0$ are by definition the terrestrial ones (Nier 1950). At the right of Table 4 we give the weighted mean wavelength for each mixture. This weighted mean corresponds to the centroid wavelength of the λ3984 complex for mix q in the absence of saturation effects.

b) λ_c *versus* W_λ *Diagram*

To generate line profiles, the line depth at frequency ν in the composite isotopic complex,

$$A_\nu = A_0 \frac{\eta_\nu}{1 + \eta_\nu} ,$$

was calculated by use of a Milne-Eddington model in LTE for which η_ν, the ratio of line to continuous opacity, is expressed as the sum of contributions of isotopic and hyperfine components, i.e.,

$$\eta_\nu = \eta \phi_\nu , \qquad (4)$$

where

$$\phi_\nu = \sum_i g_i H(a, v_i)/\sqrt{\pi} \qquad (5)$$

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1976ApJ...204..131W

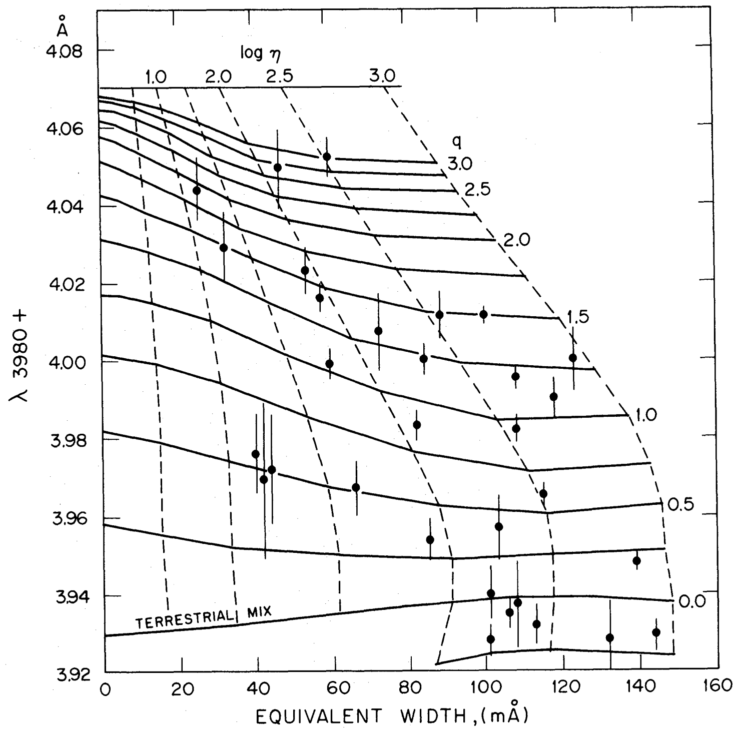

FIG. 5.—The λ_c versus W_λ diagram. Solid and dashed curves are contours of constant q and log η used to construct theoretical profiles as described in the text.

and

$$\int \phi_v dv = 1 \, . \tag{6}$$

$H(a, v)$ is the Voigt profile in standard notation and g_i is the fractional abundance from Table 4 ($\sum g_i = 1$). For simplicity all calculations were made with the damping constant $\Gamma = 1.4 \times 10^9 \text{ s}^{-1} (=10\Gamma_{cl})$, $B_0/B_1 = 2/3$, $T = 11{,}500$ K, and zero microturbulence in the line-forming region. For chosen q and η, A_v was calculated at numerous frequencies across the line complex, and λ_c and W_λ were obtained by numerical integration. The λ_c versus W_λ relations obtained for the mixtures in Table 4 are superposed on the observed data in Figure 5. Dashed lines indicate contours of constant η, while solid lines are contours of constant q. The behavior of the curve for $q = 2$ illustrates the effects of saturation. Because $g_{204} = 0.91$ in this case, the 204 component saturates at small W_λ. Further increase in W_λ due to growth of components of shorter wavelength is accompanied by shifts as large as 0.03 Å. The damping wings of 204 reverse the trend at large W_λ. The shifts due to saturation reverse direction for $q \lesssim 0.2$. Thus the effect of saturation is to compress the observed range of λ_c.

c) *q versus T_e Diagram*

Values of q and log η interpolated from Figure 5 are listed in Table 1. The plot of q versus T_e in Figure 6 illustrates, within the framework of our hypothesis, the degree of fractionation that has occurred in each

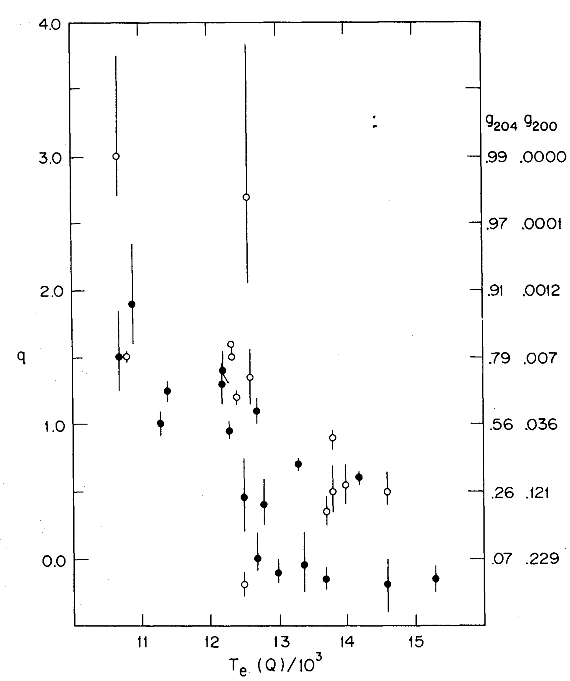

FIG. 6.—The q versus T_e diagram. The values of q and their error bars were interpolated from Fig. 6. Coding is as in Fig. 3.

1976ApJ...204..131W

star. The departures from terrestrial abundances ($q = 0$) are indicated by the fractional abundances for ^{200}Hg and ^{204}Hg indicated at the right side of Figure 6: for $q \gtrsim 1$ they are very large. Slightly negative q-values are required to explain the seven stars that define the lower bound in the range $12{,}500 < T_e < 16{,}000$ K, but this result is sensitive to small errors in both the laboratory and stellar wavelengths. The separations of the isotopic components were well determined by Mrozowski, but the absolute wavelengths are based entirely on an old measurement by Cardaun (1914) that should be repeated. The correlation of q with T_e simply reflects the correlation between λ_c and T_e in Figure 3. Finally, we note without explanation a tendency for components of binaries to lie systematically above single stars in Figure 6 (2 Per is a glaring exception). This tendency is most pronounced at $T_e \gtrsim 13{,}000$ K where five of seven stars with $q > 0$ are members of binaries.

d) Hg *Abundances*

The values of log Nf for Hg in Table 1 were calculated from the log η's by use of values of P_e, T, and κ_{4000} at $\tau = 0.25$ that were interpolated from the models of Strom and Avrett (1966). If Dworetsky's (1971) $f_{3984} \approx 3 \times 10^{-3}$ is correct and Cameron's (1968) terrestrial abundance log N(Hg) $= 1.4$(log N(H) $= 12$) is the normal cosmic value, then the stellar overabundance factors are rather uniformly distributed over the range 6×10^3 to 4×10^5. We find no discernible correlation between abundance and either T_e or q.

e) *Line Profiles*

The interferometric line profiles provide a consistency test of the validity of our analysis. Theoretical line profiles are superposed on the observed profiles of three stars in Figure 2. The profiles, computed from equations (3), (4), and (5), were broadened by convolutions with the rotational broadening function for limb-darkening coefficient $\beta = 3/2$ and an instrumental broadening function (an Airy function was chosen to approximate the Fabry-Perot transmittance function). *The adopted values of q are those taken from Figure 5.* The value of $v \sin i$ was adjusted to optimize the fit, but in each case the adopted $v \sin i$ is close to the value estimated from spectrograms. In order to fit the observed profiles it was necessary in each case to use a slightly larger value of η than that inferred from the photographic data.

The profiles computed by this procedure agree well with the observed ones to within the estimated uncertainties of the observations. From this, we conclude that the abundance mixes generated by equation (2) are reasonably realistic approximations to the actual stellar mixes.

V. DISCUSSION

We have shown that the wavelengths of λ3984 in Hg stars are distributed continuously from the value for the terrestrial mix to values that require large relative overabundances of the heavier isotopes. We believe it unlikely that this range is a spurious one produced by an unknown contributor of variable strength at λ3984.

The isotope anomalies for ι CrB and HR 4072 indicate that severe fractionation has occurred in their atmospheres. We have used this fact to generate a scheme by which degrees of fractionation can be inferred from measured wavelengths and equivalent widths. The q versus T_e diagram indicates that the degree of fractionation is systematically larger in the cooler stars of our sample.

Michaud *et al.* (1974) claim that they can produce the entire range of isotopic abundances encountered in Hg stars by diffusion under the action of radiation pressure. According to them apparent overabundances of the heavier isotopes can be produced by "hiding" large fractions of the lighter isotopes in the doubly ionized state at very small optical depths under special conditions. The conditions must change with T_e to produce the q versus T_e diagram. We can think of no alternatives to their proposal, but we do not believe it worthwhile to compare our results with their predictions in any detail until their plausible but arbitrary estimates of the ionization equilibrium and radiation forces for Hg II and Hg III at small τ are verified.

One crucial experiment deserves mention—namely, the attempt to detect the large amounts of Hg III predicted by Michaud *et al.* (e.g., $N_{\rm III}/N_{\rm II} > 10$ for χ Lup). Numerous ultraviolet transitions of Hg III longward of the Lyman limit that arise from 5 eV to 10 eV levels (Johns 1937; Foster 1950) would be candidates for observation by an orbiting spectrometer.

We are indebted to Dr. Gerald Wasserberg and his colleagues at the Caltech Lunatic Asylum for suggesting that we investigate the mass dependence of the separation factor. We also wish to acknowledge the many careful wavelength measurements made by Miss Sylvia Burd. One of us (R. E. W.) performed part of this research while he was a National Academy of Sciences–National Research Council Resident Research Associate.

REFERENCES

Bidelman, W. P. 1962, quoted in *Sky and Tel.*, **23**, 140.
———. 1966, in *Abundance Determinations in Stellar Spectra*, ed. H. Hubenet (New York: Academic Press), p. 229.
Blanco, V. M., Demers, S., Douglass, G. G., and FitzGerald, M. P. 1970, *Pub. U.S. Naval Obs.*, Vol. **21**.
Cameron, A. G. W. 1968, in *Origin and Distribution of the Elements*, ed. L. H. Ahrens (New York: Pergamon Press), p. 125.
Cameron, A. G. W. 1971, *Pub. A.S.P.*, **83**, 585.
Cardaun, L. 1914, *Zs. f. Wiss. Phot.*, **14**, 56 and 89.
Cowley, A. P. 1972, *A.J.*, **77**, 750.
Cowley, A., Cowley, C., Jaschek, M., and Jaschek, C. 1969, *A.J.*, **74**, 375.
Dworetsky, M. 1971, thesis, UCLA.
Dworetsky, M., Ross, J., and Aller, L. 1970, *Bull. AAS*, **2**, 311.
Dworetsky, M. and Vaughan, A. H. 1973, *Ap. J.*, **181**, 811.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1976ApJ...204..131W

Foster, E. W. 1950, *Proc. Roy. Soc. London, A*, **200**, 429.
Guthrie, B. N. G. 1971, *Ap. and Space Sci.*, **10**, 156.
Johns, M. W. 1937, *Canadian J. Res.* (*A*), **15**, 193.
Meggers, W. F., Corliss, C. H., and Scribner, B. F. 1961, *NBS Monog. No.* 32.
Michaud, G., Reeves, H., and Charland, Y. 1974, *Astr. and Ap.*, **37**, 313.
Moore, C. E. 1945, *Contr. Princeton Univ. Obs.*, No. 20.
———. 1968, *NBS Spec. Pub.*, No. 306.
———. 1969, *ibid.*, Nos. 306-2 through 4.
Mrozowski, S. 1940, *Phys. Rev.*, **57**, 207.
Nier, A. O. 1950, *Phys. Rev.* **79** 450.
Osawa, K. 1965, *Ann. Tokyo Astron. Obs.* (2d Ser.), **9**, 123.
Paschen, F. 1928, *Sitz. der Preuss. Akad. der Wiss.* (Phys.-Math.), **32**, 536.
Penkin, N. P. 1964., *J. Quant. Spectrosc. and Rad. Transf.*, **4** 41.
Preston, G. W. 1971, *Ap. J.* (*Letters*), **164**, L41.
———. 1974, *Ann. Rev. Astr. and Ap.*, **12**, 257.
Preston, G., Vaughan, A., White, R., and Swings, J. P. 1971, *Pub. A.S.P.*, **83**, 607.
Schild, R., Peterson, D., and Oke, J. B. 1971, *Ap. J.*, **166**, 95.
Strom, S. E. and Avrett, E. H. 1965, *Ap. J. Suppl.*, **12**, 1.
White, H. E. 1934, *Introduction to Atomic Spectra* (New York: McGraw-Hill), p. 331.

G. W. Preston and A. H. Vaughan, Jr.: Hale Observatories, 813 Santa Barbara Street, Pasadena, CA 91101

J. P. Swings: Institute d'Astrophysique, Université de Liège, 5 Avenue de Cointe, B-4200, Cointe-Ougree, Belgium

Richard E. White: Department of Astronomy, Clark Science Center, Smith College, Northampton, MA 01060

© American Astronomical Society • Provided by the NASA Astrophysics Data System